THE HOLLYWOOD STRATEGY FOR MICROLENSING DETECTION OF PLANETS

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Abstract

Follow the big stars! I review the theory of detection and parameter measurement of planetary systems by follow-up observations of ongoing microlensing events. Two parameters can generically be measured from the event itself: the planet/star mass ratio, q, and the planet/star separation in units of the Einstein ring. I emphasize the advantages of monitoring events with giant-star sources which are brighter (thus easier to monitor) and bigger (thus offering the prospect of measuring an additional parameter from finite-source effects: the proper motion μ). There is potentially a strong degeneracy between q and μ. I present a simple analytic representation of this degeneracy. I then describe how it can be broken using accurate single-band photometry from observatories around the world, or optical/infrared photometry from a single site, or preferably both. Both types of observations are underway or will be soon. Monitoring of giant-star events seen toward the bulge is also the best way to determine the content and structure of the inner Galaxy.

1 Introduction

Two world-wide networks are currently searching for extra-solar planetary systems by making densely sampled observations of ongoing microlensing events toward the Galactic bulge (PLANET [2]; GMAN [18]). Several other groups will join the search shortly and there is serious discussion of new initiatives that would intensify the search by an order of magnitude. More than 100 microlensing events have been detected to date by three groups, MACHO [3], OGLE [21], and DUO [1], based on observations made once or twice per night. The events typically last one week to a few months. MACHO and OGLE have reported “alerts”, events detected before peak. This alert capability is what has allowed PLANET and GMAN to make intensive, sometimes round-the-clock, follow-up observations in hopes of finding the planetary perturbations which are expected to last a day or less. EROS [4] will shortly initiate a search for bulge microlensing events using a new 1 square-degree camera which should more than double the number of alerts.

In sharp contrast to this explosion of observational activity, theoretical work on planet detection has been rather sparse, amounting to only five papers in as many years. Mao & Paczyński (1991) originally suggested that planets might be detected in microlensing events [17]. Gould & Loeb (1992) developed a formalism for understanding the character of planetary perturbations and made systematic estimates of the rate of detection for various planetary-system parameters [14]. Bolatto & Falco (1994) studied the detection rate in the more general context of binary systems [6].

Early work assumed that the lensed star could be treated as a point source. The usefulness of this approximation depends primarily on ρ, the ratio of the angular size of the source, θ_*, to the planetary Einstein ring, θ_p,

$$\rho = \frac{\theta_*}{\theta_p}, \qquad \theta_p = \sqrt{q}\theta_e, \qquad q = \frac{m}{M}, \qquad \theta_e = \sqrt{\frac{4GMD_{\rm ls}}{c^2 D_{\rm ol} D_{\rm os}}}. \tag{1}$$

Here θ_e is the Einstein ring of the lensing star, m and M are the masses of the planet and its parent star, and $D_{\rm ol}$, $D_{\rm ls}$, and $D_{\rm os}$ are the distances between the observer, lens, and source. For Jupiter-mass planets at typical distances ($D_{\rm ls} \sim 2\,{\rm kpc}$) from bulge giant sources, $\theta_p \sim 3\theta_*$, so the approximation is a reasonable one. However, for Saturns, Neptunes, and especially Earths, the finite size of the source becomes quite important, and even for Jupiters it is not completely negligible. Moreover, as I will stress below, it is quite possible to mistake a "Jupiter event" in which the source size is negligible for a "Neptune event" with $\theta_* > \theta_p$. Hence it is essential to understand finite-source effects even to interpret events where the source size is in fact small.

Progress on finite-source effects was substantially delayed by problems of computation. Like all binary lenses, planetary-systems have caustics, curves in the source plane where a point-source is infinitely magnified as two images either appear or disappear. If one attempts to integrate the magnification of a finite source that crosses a caustic, one is plagued with numerical instabilities near the caustic. While it is straight forward to solve these problems for any given geometry, the broad range of possible geometries makes it difficult to develop an algorithm sufficiently robust for a statistical study of lensing events. Bennett & Rhie (1996) solved this problem by integrating in the image plane (where the variation of the magnification is smooth) rather than the source plane (where it is discontinuous) [5]. They were thereby able to investigate for the first time the detectability of Earth to Neptune mass planets. Gould & Gaucherel (1996) showed that this approach could be simplified from a two-dimensional integral over the image of the source to a one-dimensional integral over its boundary [12]. The difficult computational problems originally posed by finite-source effects are now completely solved.

2 The Chang-Refsdal Formalism

Gould & Loeb analyzed the problem of planet detection by treating the planet as a perturbation on a uniform background shear, γ, produced by the star [14]. Let x be the source-lens separation in units of θ_e. Then the two images are at $y_\pm$ with respectively shears $\gamma_\pm$ and magnifications $A_\pm$,

$$\gamma_\pm = y_\pm^{-2}, \qquad y_\pm = \frac{\sqrt{x^2+4}\pm x}{2}, \qquad A_\pm = \frac{1}{|1-\gamma_\pm^2|}. \tag{2}$$

Since the two unperturbed images are separated by $> 2\theta_e$, while the effective range of the planet is only $\sim \theta_p$, the planet can affect at most one image. The Gould-Loeb approach is to treat the other image as unperturbed with magnification given by equation 2 and to focus the analysis on the perturbed image. This image is treated as a Chang-Refsdal lens [7] [20], a point mass superposed on a constant background shear. The shear is chosen as the shear at the position of the unperturbed image at the midpoint of the perturbation. The actual shear due to the lensing star is, of course, not the same at the unperturbed and perturbed positions of the images and also varies with time during the planetary perturbation. Nevertheless, because the range of the planet's effect is small, the errors induced by this approximation are negligibly small [8].

The Chang-Refsdal approximation immeasurably simplifies the analysis of planetary lensing events. To lowest order, one measures 6 parameters of a planetary-system light curve,

$$t_0, \qquad \beta, \qquad t_e, \qquad x_d, \qquad \delta_d, \qquad t_d, \tag{3}$$

The first three are the parameters of the unperturbed event, its time of maximum, impact parameter in units of θ_e, and Einstein crossing time. The next three describe the gross features of the planetary perturbation, the source-lens separation at the midpoint of the perturbation, the maximum fractional deviation from a standard light curve, and the full-width half-maximum (FWHM). The value of γ can then be computed up to a two-fold ambiguity $\gamma = \gamma_\pm(x_d)$ using equation 2. The two cases are easily distinguished provided there is reasonable coverage of the light curve because perturbations of the minor ($-$) image have a large negative excursion surrounded by positive excursions while

perturbations of the major (+) image are positive in the middle [14] [5] [8]. I focus here mainly on the major-image perturbation because it occurs more frequently and is somewhat easier to understand.

The two-dimensional structure of the magnification contours (up to an overall scale factor $q^{1/2}$) is fixed by this determination of γ [14] [8]. The angle at which the source traverses this structure is given by $\sin\phi = \beta/x_d$. There remain three unknowns: q, ρ, and α, where the last is the planet/unperturbed-image separation in units of θ_p.

3 Point Sources

Suppose that the source were somehow known to be small compared to the planet Einstein ring, $\rho \ll 1$. If the source passed outside the caustic region, the perturbation would be characterized by a smooth bump. By comparing the observed height of the bump δ_d with the height of the perturbation ridge, one could determine the planet/unperturbed-image separation up to a two-fold ambiguity $\pm\alpha$. The combination of observables

$$Q = \left(\sin\phi \frac{t_d}{2t_e}\right)^2, \tag{4}$$

could then be compared with the FWHM of the perturbation contours at α to determine q. For ease of illustration, I will assume here that this FWHM is $2\theta_p$ (which is a good general approximation). In any event, it is no trouble to calculate the exact value for any particular case. For this choice,

$$q = Q, \qquad \rho \ll 1. \tag{5}$$

The planet/star separation in units of the Einstein ring is then $y_p = y_+(x_d) \pm \alpha q^{1/2}$. Thus, the fractional uncertainty in the separation is $\sim 2\alpha q^{1/2}$. For example, for $q = 10^{-3}$ (as with Jupiter and the Sun) and $\alpha = 10$ (which is not at all atypical) this uncertainty would be $\sim 60\%$. This degeneracy can be broken from the asymmetry of the perturbation. If, for example, the perturbation takes place after the peak of the event, then the planet is closer to (farther from) the lens than y_+ if the leading wing of the perturbation is higher (lower) than the trailing wing.

If the source passed over or very close to the caustic, it would be possible to determine q, ρ, and α just as it is for all other binary-lens caustic-crossing events.

4 Degeneracy From Finite Source Effects

If $\delta_d \ll 1$, then one possible cause is that $\alpha \gg 1$. However, another possible cause is that $\rho \gg 1$. In fact, for $\alpha = 0$ and a source which is larger than the caustic structure, Gould & Gaucherel find analytically that the fractional deviation of the major image is [12]

$$\delta_d = \frac{2}{\rho^2 A(\gamma)} + \mathcal{O}(\rho^{-4}), \qquad A(\gamma) = \frac{1+\gamma^2}{1-\gamma^2}. \tag{6}$$

[For the minor image, $\delta_d \sim \mathcal{O}(\rho^{-4})$.] If $\rho \gtrsim 1$, then the duration of the perturbation is set by the size of the source, not the planet Einstein ring. The net result is that the solution

$$q \sim \frac{Q}{\rho_{\max}^2}, \qquad \rho \sim \rho_{\max} = \sqrt{\frac{2}{\delta_d}\frac{1-\gamma^2}{1+\gamma^2}}, \tag{7}$$

reproduces the peak and FWHM just as well as equation 5. Intermediate solutions are also allowed. Since one hopes to detect planetary systems with deviations at least as small as $\sim 5\%$, this degeneracy can be rather severe. For example, for $\gamma = 0.6$, the range of allowed masses is $\sim \delta_d^{-1}$ or ~ 20 for $\delta_d \sim 5\%$. For high mass planets ($\rho < 1$) some events will have $\delta_d \sim 1$ in which case there is no mass degeneracy. However, most will have $\delta_d < 1$ and, if the degeneracy is not broken, these can be confused with planets of much lower mass ratios. Moreover, for low mass planets, one always has $\delta_d < 1$, so these can never be unambiguously identified without breaking the degeneracy.

5 Breaking the Mass Degeneracy

There are essentially two methods for breaking this degeneracy: detailed light curves and optical/infrared photometry. If a point source ($\rho \ll 1$) passes far from the planet ($\alpha \gg 1$), then the wings of the deviation will show a smooth rise and fall. On the other hand, if a large source ($\rho \gtrsim 1$) passes over the caustic ($\alpha \lesssim 1$), the leading wing will show a slight fall and then an abrupt rise as the source passes over regions of negative deviation and then infinite magnification. The trailing wing shows the same behavior in reverse. The difference between these two curves is typically of order a few per cent and is concentrated in two brief intervals (typically a few hours) on either side of the peak. Thus, both accurate photometry and good weather at the appropriate observing station at the right time are required.

A second method is to use simultaneous optical/infrared (e.g. V and H) photometry. Since giant stars are more limb-darkened at bluer wavelengths, the light curve will show color variations if the source passes over (and is therefore resolved by) a caustic. When the red leading edge passes over the caustic, the image becomes red. At the peak it becomes blue, then red again. For a point source passing far from the planet, there are no color changes. Since the color changes are smaller, $\sim 1-2\%$, this method requires even better photometry. Moreover, it requires specialized equipment in order to observe simultaneously in optical and infrared light. However, the color variations occur at all phases of the deviation, so no special observing luck is required. Finally, the specialized camera has been approved by the US NSF and should be ready by the bulge season of 1998 (private communication, D. DePoy 1996). Probably, the best solution is to combine continuous round-the-clock coverage with optical/infrared photometry from at least one site.

If the degeneracy is broken, then one measures at least two parameters, q and y_p. If the source passes over the caustic, or if $\rho > 1$, then one measures a third parameter, ρ. Note that in this case, one also determines the proper motion μ,

$$\mu = \frac{\theta_*}{\rho t_e \sqrt{q}}. \tag{8}$$

6 From Mass Ratios to Masses

From t_e alone, one can estimate M and $r_e = D_{\rm ol}\theta_e$ only to about a factor of 3. Consequently, even if q and y_p are determined unambiguously, the mass $m = qM$ and physical projected separation $a_p = r_e y_p$ are in general only known to a factor 3. If μ is measured, these uncertainties are reduced to about a factor 2. As mentioned above, μ can be measured for most planetary events for which $\rho \gtrsim 1$. Using equation 1, one finds that this occurs provided

$$m > 30\, M_\oplus \frac{D_{\rm ol}/D_{\rm ls}}{3} \left(\frac{r_*}{10\, r_\odot}\right)^2, \tag{9}$$

where r_* is the radius of the source. Recall that it can also be measured for larger planets provided that the source crosses the caustic.

If a parallax satellite [19] [9] were launched, it could routinely measure the projected Einstein radius $\tilde{r}_e = (D_{\rm os}/D_{\rm ls}) r_e$ [13]. This by itself would dramatically reduce the uncertainties in M and r_e [16] and so in m and a_p. Moreover, if μ (or ρ) were also measured, the planet mass and projected separation would be determined [10],

$$m = \frac{c^2}{4G} \frac{\theta_* \tilde{r}_e \sqrt{q}}{\rho}, \qquad a_p = \frac{y_p}{\tilde{r}_e^{-1} + \rho\sqrt{q}/r_*}. \tag{10}$$

7 Giants Rule

For some time, I have been advocating that microlensing searches toward the bulge focus primarily on giants [10]. This view is motivated primarily by a desire to understand the structure and content of the Galaxy. Giant events can be detected in R band even for $A_R = 4.5$ ($A_V = 5.7$), and so could be found in all but the most heavily extincted regions of the bulge. They are not crowded, so they are hardly affected by blending. In addition, they suffer no significant bias toward monitoring stars on the near side of the bulge compared to the far side. These factors mean that the observed optical depths and time scales of detected events do not require large and uncertain corrections as a function of position. In addition, the blending suffered by turnoff stars generates a large tail of spurious short events [15] and even if one had confidence in the statistical corrections to this effect, it would be difficult to unambiguously detect or rule out a large brown dwarf population in the bulge using these sources. Finally, it is possible to measure the proper motions of a much bigger fraction of giant star than turnoff events both because they are larger (and so more often give rise to finite source effects) and they are brighter, especially in the infrared where their two images can sometimes be resolved using interferometry [11].

Are giant sources also better for planet searches? The question is important because the same follow-up observations are used both to detect planets and probe Galactic structure. I believe the answer to this question is: Yes, definitely. First, giants are brighter and hence easier to monitor. Since dozens of stars must be monitored simultaneously, bright sources (and hence short exposures) are highly valued. Second, giants can be seen even in the relatively heavily obscured central portions of the Galaxy where there are likely to be more lensing events. Third, while it is true that the peak deviation is suppressed when a giant is lensed by a small planet, the onset of this effect is only at $m \lesssim 30\, M_\oplus$ for planets in the bulge, and $m \lesssim 10\, M_\oplus$ for planets in the disk (see eq. 9). Moreover, suppression for these small-mass planets does not become severe until one reaches masses that are a factor 3–10 lower. And these events with suppressed peaks have several compensating advantages including measurement of μ and a higher event rate due to a larger cross section. It is true that for Earth-mass planets, the suppression can be so severe that the event is missed altogether [5]. Thus, to detect Earth-mass planets, it may in fact be necessary to monitor turn-off stars. The cross sections for Earth-mass planets are so low that there are probably not enough giants available to monitor to detect Earth-mass planets anyway. Hence, they require an order-of-magnitude larger search than is likely to be conducted in the near future, with more and larger follow-up telescopes so that many hundreds of faint-star lensing events can be followed on one-hour time scales. For the present, giant sources are the indicated choice.

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